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AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

A Total Radiation Fluxmeter

by

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I. Introduction

This instrument is designed to measure the net flow of radiation through a horizontal surface. In principle the method of doing this is quite simple; one has only to place a horizontal plate, which is blackened on both surfaces, in this radiation field and then to measure the temperature difference between the upper and lower surface (see appendix I). The problem is complicated somewhat when a device of this sort is used in the open for meteorological purposes, firstly, because of the wide range of wavelength to which the instrument must respond with equal sensitivity and secondly, because a means must be found to eliminate the effect of the wind blowing on the plate and causing large variations in the energy interchange between the surfaces of the plate and the air. It is not possible to enclose the plate completely whilst still satisfying the first requirement, because there is no readily available material equally transparent over the wavelength range of meteorological interest, i.e. from about 0.3 μ to beyond 40 μ. The device for overcoming this difficulty is to ensure, by artificial means, that the plate is always operating in a blast of air. This sustained blast, directed equally over the plate, keeps the energy interchange between the surfaces of the plate and the air at a high level which is not appreciably altered when the free wind varies. With this radiometer the response is kept constant to 2% in winds up to 20 m.p.h. Instruments of this type have been constructed by G. Falkenberg (1) and independently by W. Mörikofer (2) and J.T. Gier (3). In G. Falkenberg's "vibration-pyranometer" the effect was obtained by rapidly vibrating the horizontal plate in its own plane, so that even under calm conditions it was effectively operating in rapidly moving air. The other two instruments used a stationary plate ventilated by a small blower. The instrument to be described is very similar to J.T. Gier's which is now produced commercially in the U.S.A. As the instrument is by no means new the emphasis of this paper is on the special problems of calibration and an examination of its behaviour in use.

II. Construction

(a) General

The instrument consists of three parts: the radiation sensitive element in the form of a thin 3 in. square plate, a blower to maintain the steady blast of air, a nozzle which directs the air from the blower symmetrically over the upper and lower surfaces of the element. A photograph of the complete

/radiometer

radiometer is shown in figure 1 and the radiometer is drawn to scale in figure 2. It will be noticed that the sides of the nozzle are extended alongside the element by two side plates marked D D^1 in figure 2. The function of these is to constrain the air flow over the element and to provide a little protection against deflection of the blast by broadside winds. W. Mörikofer at the 1951 U.G.G.I. meeting maintained that it was essential to use an aerodynamically-shaped nozzle and an element in the form of an aerofoil. This instrument is not aerodynamically designed but it was found most important for the disposition of the element, side plates and nozzle mouth to be symmetrical about a plane through the centre of the element. Any inaccuracy in this arrangement, or any asymmetry in the design of one of these parts, will lead to incomplete wind compensation (see III (a)). Power for the blower was drawn from the mains and regulated with a simple carbon pile voltage regulator to 24±1 volts. A variation in the voltage of this size was found to keep the ventilation velocity constant to 0.7%.

(b) The Sensitive Element

Figure 3 shows the radiometer element in more detail. It has a sandwich-like structure, bakelite in the centre with 1/100 in. sheet aluminium on top and bottom. The aluminium surfaces are separated from the bakelite core by thin sheet polythene. Two slots are cut out of the central bakelite sheet forming a frame for the thermopile. This is made by winding about 60 turns of 46 S.W.G. constantan wire around bakelite strips whose size is slightly smaller than the slots in the bakelite frame. One half of each turn of wire on the strips is copper plated, so that a series of copper-constantan thermojunctions is formed down the centre line of the top and bottom surfaces of each strip. These thermopile strips fit inside the bakelite frame and the connections between the strips and to the external leads are made to the copper plated part of the last turn on each strip. The whole sandwich is stuck together with Everett's wax. When the element is mounted in position at the mouth of the nozzle, Parson's optical black is used to paint the aluminium surfaces.

III. Characteristics of the Radiometer

(a) Effect of wind speed on the sensitivity

The effect of wind was examined in the laboratory by placing the radiometer in a crude wind tunnel formed by the floor, a large horizontal plane and a powerful blower. By altering the distance between the radiometer and this blower different wind speeds could be simulated. A 2000 watt tungsten filament lamp, whose supply was hand regulated, provided a constant source of radiation. In figure 5 is shown the arrangement for this experiment. Two positions of the radiometer were tested:

A. Wind in opposition to radiometer ventilation.
B. Wind at right angles to radiometer ventilation.

In figure 6 the percentage change in the output of the radiometer is plotted against the wind speed for the two positions A and B. The dotted curve shows the result of a similar experiment performed by G. Falkenberg with his "vibration pyranometer", and table I gives J.T. Gier's figures.

TABLE I

Position A		Position B	
Wind speed m.p.h.	% change	Wind speed m.p.h.	% change
5.7	4.8	7.3	-2.5
11.4	0.0	9.8	-3.4
15.0	-2.5	15.3	-4.2
19.8	-16.0	20.5	-6.3
25.0	-11.0	23.6	-8.3
27.6	-11.0		

/During

During the course of this experiment the importance of correctly aligning the position of the element, nozzle and side plates was discovered. More extensive wind tunnel tests were performed with a mark II instrument of larger design and without the protective side plates. This instrument was tested in position B (see above). If the radiometer blast of air is moving south then the wind directions used were east and west. In each run the surface of the radiometer was set horizontal with a small spirit level and the four possible positions for the radiometer, satisfying the general classification B, were tried. For each of these four positions the lamp was moved from above the radiometer to below it. The reasons for all these different positions were:
(a) although it is simple to set the radiometer surface horizontal it was not certain that the flow of air in the wind tunnel was truly horizontal,
(b) to find if a difference existed between effect of an E. and W. wind,
(c) to find if there was an effect depending on the direction of flux through the radiometer. By taking means of experiments done under identical conditions with respect to coordinates fixed on the radiometer, any contribution due to a wind component perpendicular to the element could be eliminated. From these results the effect for an east and west wind was deduced, and little effect due to flux direction was found. Unfortunately it was not possible to estimate the angle between the wind tunnel stream and the horizontal, but its effects were not significant below wind speeds of 16 m.p.h. and even then were only of the order of 1%. In table II are the results of this experiment. Each table is labelled with respect to axes fixed in the radiometer. It is assumed that the wind tunnel flow, which is nominally parallel to the radiometer element, has a component perpendicular to the element. Each experiment is classified X or Y according to whether this component is in the same direction or the opposite direction to the flow of radiation. Then the mean of run 1 and run 3a gives the true effect of an east windwith positive flux. The mean of run 1a and run 3 gives the effect of an east wind with negative flux. Similarly for the west wind runs.

TABLE II

East Wind Runs

Wind Speed	Run 1 East Wind +ve flux Class X	Run 1a East Wind -ve flux Class Y	Run 3a East Wind +ve flux Class Y	Run 3 East Wind -ve flux Class X	Mean of Runs 1, 3a East Wind +ve flux	Mean of Runs 1a, 3 East Wind -ve flux
m.p.h.	%	%	%	%	%	%
00.0	100	100	100	100	100	100
05.0	100.4	99.5	99.4	99.8	99.2	99.7
10.2	99.9	98.9	99.4	99.8	99.2	99.4
16.0	98.5	98.7	99.6	97.2	99.0	98.0
20.5	97.8	98.7	100.3	98.8	99.0	98.8
24.5	96.6	101.5	101.5	99.4	99.0	100.5
29.3	97.7	103.1	102.6	100.5	100.1	101.8
34.5		102.6		100.5		

West Wind Runs

Wind Speed	Run 2 West Wind +ve flux Class Y	Run 2a West Wind -ve flux Class X	Run 4a West Wind +ve flux Class X	Run 4 West Wind -ve flux Class Y	Mean of Runs 2, 4a West Wind +ve flux	Mean of Runs 2a, 4 West Wind -ve flux
m.p.h.	%	%	%	%	%	%
00.0	100	100	100	100	100	100
05.0	99.4	99.8	100.2	99.4	99.8	99.6
10.2	99.0	100.0	99.8	99.2	99.4	99.6
16.0	98.6	98.6	98.6	98.4	98.6	98.5
20.5	96.9	95.8	98.3	98.4	97.6	97.1
24.5	97.6	95.8	97.3	98.7	97.5	97.3
29.3	97.7	96.6	98.1	98.8	97.9	97.7

/(b)

(b) The aperture of the Radiometer

The amount of the sphere that can be "seen" by the element is defined on two sides by the side plates and on the third side by the leading edge of the nozzle; the fourth side is unobstructed. Figure 4 shows how on three sides the sensitive central area of the element will only partly "see" portions of the upper hemisphere between +22° and +6° elevation, similarly for the lower hemisphere. No radiation within 6° above and below the horizon is accepted on these three sides. If the radiometer were placed in a field of radiation isotropic over the upper hemisphere, the calculation in appendix II shows that its effective aperture is 97% of the hemisphere. When used in daytime it is undesirable for the shadow of the side plates to be too near the central sensitive area. This instrument was only required to work for periods of about one hour, so it was orientated according to the sun's position.

(c) The paint

The upper and lower surfaces of the radiometer element were painted with Parson's optical black. As was explained in the introduction, this instrument must respond with equal sensitivity over the wavelength range from about 0.3 μ to beyond 40 μ . The emissivity of this paint was determined by the N.P.L. in the visual range and for black body radiation at 2580°C, 1000°C, 200°C. In paragraph IVa it will be shown (equation 3) how, during the course of the calibration, the emissivity of a piece of tinned copper painted with Parson's optical black is determined. The results of this work are shown in table III:

TABLE III

λ max	0.5 μ	1.1 μ	2.4 μ	6.3 μ	10.0 μ
Black Body Temperature	Visual	2580°C	1000°C	200°C	25°C
Emissivity	0.985	0.985	0.980	0.985	0.98
Work done at:	N.P.L.	N.P.L.	N.P.L.	N.P.L.	Kew

(d) Cosine Law for surface of Radiometer

When the radiometer is placed in a parallel beam of radiation, the output should be proportional to the cosine of the angle of incidence. Figure 7 shows that this law is obeyed quite well.

IV. Calibration of the Radiometer

For meteorological work this instrument must be equally sensitive to radiation in the wavelength range from about 0.3 μ to 40 μ . The paint used for the surface of the element did not show any appreciable variation of emissivity with wavelength. It was still considered necessary to determine the sensitivity of the radiometer when used in fields of long wave (> 3 μ) and short wave (roughly 0.3 μ to 3 μ) radiation, both in the laboratory and in the open. Four separate methods were used, two of them, (a) and (b), in the laboratory with long and short wave radiation respectively. The other two methods were both done in the field, (c) at night when the radiation is long wave only, and (d) during daytime when the radiation is a mixture of long wave atmospheric and terrestrial radiation with short wave solar and sky radiation. The results of these four methods are tabulated in table IV:

/TABLE IV

TABLE IV

	Laboratory Long Wave	Laboratory Short Wave	Field Long Wave	Field Long and Short Wave
Sensitivity μV/m.watt cm^{-2}	$66^{+}_{-}1$	$71^{+}_{-}1$	$67.4^{+}_{-}0.6$	$68^{+}_{-}1$
		Mean $68^{+}_{-}1$		

(a) Laboratory calibration with long wave radiation

One of the difficulties in calibrating a radiometer with the radiation of a "low" temperature body is to keep radiation from the surroundings constant, also care must be taken to see that no heat is convected (either forced or natural) from the body to one surface of the radiometer. To these ends a copper calibrating box, shown in figure 8, was constructed. This box was painted black on the inside and covered with felt on the outside. In the top of this box a square aperture B was cut and holes were made at each end; one, C, just large enough to allow the radiometer to be placed directly underneath the aperture, the other hole, D, was made to allow air blown through the radiometer to escape. Flaps E E^{1} were fitted to the edges of this latter hole and were adjusted so that there was no flow of air through the aperture B when the radiometer was in position and blowing. This condition was determined by placing a thin sheet of paper over the aperture. The efficiency of the box as a radiation enclosure was tested by placing a shutter over the aperture and measuring the output of the radiometer over 24 hours. If left undisturbed for 2 min. to 3 min. the box was found to be effective in so much that it reduced any flux inside the box to less than 0.01 m.watts cm.$^{-2}$. A large cavity black body, used by W.H. Dines, was placed over the aperture. One junction of a calibrated thermocouple, X, was soldered to the calibrating box directly underneath the radiometer, the other junction, Y, was placed in the water bath which surrounded the black body. The dimensions of the aperture, sensitive element and the distance of the radiometer below the aperture were measured. From these measurements the effective aperture, which L. Bossy and R. Pastiels[4] call the "rapport surface-angle", was calculated in the manner shown in appendix II.

Now if
T_1 = Temperature of the cavity black body
T_2 = Temperature of the calibrating box
D = Output of the radiometer
ε = Emissivity of the inside surface of the box
F = Flux of radiation normal to the radiometer surface
ψ = Effective aperture as defined in appendix II
σ = Stefan's constant

Then neglecting water vapour and carbon dioxide absorption, we have:

$$F = \psi \sigma (T_1^4 - \varepsilon T_2^4) \qquad (1)$$

$$= \lambda D \quad \text{from appendix I} \qquad (2)$$

$$\text{therefore } \frac{D}{T_2^4} = \frac{\psi \sigma}{\lambda} \left[\left(\frac{T_1}{T_2} \right)^4 - \varepsilon \right] \qquad (3)$$

Now in the calibration T_1 was varied from 50°C to 25°C and T_2 varied between 20°C and 21°C.

/By plotting

By plotting

$$\frac{D}{T_2^4} \text{ against } \left(\frac{T_1}{T_2}\right)^4$$

we get a straight line and so determine λ and ε, the calibration constant of the radiometer and the emissivity of the bottom surface of the calibrating box. From the air temperature and humidity these values are corrected for the effect of water vapour and carbon dioxide absorption (5).

(b) Laboratory calibration using short wave radiation

The radiation for this calibration was produced by a 2000 watt lamp, and the intensity of the radiation was measured by means of a Linke-Feussner actinometer carefully set at the same distance from the lamp as was the radiometer. When comparing two instruments of such widely differing apertures care must be taken to see that all contributions to the radiation flux through the radiometer are accounted for by the Linke-Feussner actinometer. For although the major part of the radiation field underneath a 2000 watt tungsten filament lamp consists of the short wave radiation from the incandescent filament, there exists an appreciable field of long wave radiation due in the most part to the large and heated box which surrounds the 2000 watt lamp. To eliminate effects of this sort the radiometer was placed (as is shown in figure 9) in between two large sheets of glass, B B^1 in figure 9, which act as a filter opaque to all radiation whose wavelength is greater than about 3 μ . Any contribution to the flux of radiation due to a temperature difference between the glass sheets can be measured by reversing the position of the Linke-Feussner actinometer, pointing it first at the lamp through one glass sheet and then at the other glass sheet. The voltage to the lamp was hand regulated and a time schedule was adhered to throughout the experiment because the laboratory warmed up by 2°C during this experiment. The Linke-Feussner actinometer was itself standardised, both on the sun and in the laboratory, against the Angstrom pyrheliometer. The output of the Linke-Feussner actinometer for a radiation intensity of one g.cal.cm^{-2} $min.^{-1}$ was found by these two methods to be 10.8 ± 0.2 m.V and 10.8 ± 0.1 m.V respectively.

(c) Field method at night (Long Wave)

At night the radiation field is purely long wave radiation of atmospheric and terrestrial origin. It is only on cloudless nights, however, that the radiative flux can be measured. This is done by pointing a Linke-Feussner actinometer first at the sky and then at the ground (5) and the result of this measurement was compared with the output of the radiometer.

(d) Field method during the day (Long and Short Wave)

During the day the radiative flux consists of a mixture of short wave radiation from the sun and sky, mixed with atmospheric and terrestrial long wave radiation. The long wave component can only be measured under cloudless conditions. On these days the output of the radiometer was compared in the field with the radiative flux computed by means of a Moll solarimeter and the Linke-Feussner actinometer. By pointing the solarimeter, first at the sky and then at the ground, the flux of short wave radiation was computed. Each component of the long wave radiation was measured by two readings with the actinometer, one using a glass filter and one without the glass filter.

Conclusion

The radiometer provides a convenient method for the measurement of net radiative flux near the ground, and is particularly adapted for continuous measurement. The instrument will not function correctly in rain, or when fog develops, as the surfaces wetted would act as a "wet bulb". Prolonged exposure to rain would entail repainting and subsequent recalibration, but a few drops of rain will dry very rapidly and not cause any lasting effect.

/An

An instrument of this type has been functioning continuously for some time at Kew Observatory and during the first six months' use the calibration constants determined are ±5%.

Acknowledgments

I should like to thank Dr. G.D. Robinson for suggesting that this work should be done and for his constant advice and encouragement.

I am indebted to M.J. Blackwell and J.C. Gordon for their assistance. Valuable help with the field work was given by various members of the staff of Kew Observatory. The instrument was largely constructed in Kew Observatory workshops.

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1. G. Falkenberg. Zeit. fur Met. 1, 11/12, p. 372, (1947).

2. W. Mörikofer. Proc. of U.G.G.I., Brussels (not yet published), 1951.

3. J.T. Gier et alia. University of California, thermal radiation project report, (1949).

4. L. Bossy and R. Pastiels. Met. Inst. Roy. Met. de Belgique. Vol.29, (1948).

5. G.D. Robinson. Quart. J.R. met. Soc., 73, 315-316, (1947).

APPENDIX I (After Gier)

Theory of the instrument (after Gier et alia)

In figure 10 let

ε = emissivity of radiometer surfaces
k = thermal conductivity of bakelite
h = thermal convective conductance of air (see footnote)
T_a = air temperature
T_1 = temperature of surface 1 of radiometer
T_2 = temperature of surface 2 of radiometer

Without loss of generality we can consider the radiometer in a parallel stream of radiation, where the flux of radiation $F = G_1 - G_2$ (4)

E.M.F. produced by the thermopile $D = \mu (T_1 - T_2)$ (5)

At surface 1 we have $\varepsilon G_1 = \varepsilon\sigma T_1^4 + h (T_1 - T_a) + \frac{k}{l} (T_1 - T_2)$

At surface 2 we have $\varepsilon G_2 = \varepsilon\sigma T_2^4 + h (T_2 - T_a) - \frac{k}{l} (T_1 - T_2)$

subtracting and using (4)

$$\varepsilon F = \varepsilon\sigma (T_1^4 - T_2^4) + h (T_1 - T_2) + \frac{2k}{l} (T_1 - T_2) \quad (6)$$

as a first approximation, put $T_1^4 - T_2^4 = 4 T_1^3 (T_1 - T_2)$ (7)

$$\therefore F = \left(4\sigma T_1^3 + \frac{h}{\varepsilon} + \frac{2k}{\varepsilon l}\right) (T_1 - T_2) \quad (8)$$

$$\text{or} \quad F = \left(4\sigma T_1^3 + \frac{h}{\varepsilon} + \frac{2k}{\varepsilon l}\right) \frac{D}{\mu} = \lambda D \quad (9)$$

In order to estimate the relative importance of the three terms contained within the instrumental constant in square brackets, equation (9), put

σ = 5.7×10^{-5} erg. $cm.^{-2}$ $deg.^{-4}$ $sec.^{-1}$

ε = 1

k = 16,000 erg. $cm.^{-1}$ $sec.^{-1}$ $deg.^{-1}$

T = 300°A

l = 0.1 cm.

h = 50,000 erg. $cm.^{-2}$ $sec.^{-1}$ $deg.^{-1}$

whence

$4\sigma T_1^3$ = 6,200

$\frac{2k}{\varepsilon l}$ = 320,000

$\frac{h}{\varepsilon}$ = 50,000 (see footnote).

Consequently the temperature dependent term is effectively swamped by the other two terms.

Note

This rather unusual term "the thermal convective conductance of air" is not a property of air but of the system. It is an expression widely used by ventilation engineers and can vary within wide limits. J.T. Gier gives a

value of 50,000 erg. $cm.^{-2}$ $sec.^{-1}$ $deg.^{-1}$. An experiment done comparing the sensitivity of this radiometer when the blower was not in operation with the normal sensitivity gives a value for this system of 140,000 erg. $cm.^{-2}$ $sec.^{-1}$ $deg.^{-1}$

APPENDIX II

Effective aperture of the radiometer (Rapport surface - angle of Bossy & Pastiels)

For the laboratory low temperature calibration which is described in paragraph IVa it is required to find the mean flux through the radiometer. In figure 11 HKLM represents the aperture marked 'B' in figure 6 and ABCD is the sensitive area of the radiometer. Consider only that radiation which comes through the aperture from the black body radiator. The intensity, I, of this radiation is uniform and determined by the temperature of the water bath surrounding the black body. Consequently at P on the surface of the radiometer the flow of energy perpendicular to ABCD through the area dx dy contained in a pencil centred at P and circumscribing the area $d\xi d\eta$ about Q is dE, where $dE = I.dw.dx.dy.\cos i$

and dw = solid angle of the pencil

which $= \dfrac{d\xi.d\eta\cos i}{d^2}$

Therefore $$dE = \frac{I.\cos^2 i}{d^2}\, dx.dy.d\xi d\eta$$

$$= \frac{I.l^2}{d^4} dx.dy.d\xi d\eta$$

since $$\cos^2 i = (l/d)^2$$

or $$dE = I.l^2 \; dx.dy.d\xi d\eta \Big/ \left[(\xi-x)^2+(\eta-y)^2+\ell^2\right]^2$$

So the mean flux E through ABCD

$$E = I.l^2 \int_{-X}^{X}\int_{-Y}^{Y}\int_{-\xi_1}^{\xi_1}\int_{-\eta_1}^{\eta_1} \frac{dx\,dy\,d\xi\,d\eta}{\left[(\xi-x)^2+(\eta-y)^2+\ell^2\right]^2}$$

Now for an infinitely large aperture

$$E_H = I.l^2 \int_{-X}^{X}\int_{-Y}^{Y}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{dx\,dy\,d\xi\,d\eta}{\left[(\xi-x)^2+(\eta-y)^2+\ell^2\right]^2}$$

We now define

$$\psi = \frac{E}{E_H}$$

Using ψ we can now write down the flux through the radiometer if

T_1 = temperature of the black body over the aperture

T_2 = temperature of the calibrating box

ε = emissivity of the inside of the calibrating box

F = mean flux through the radiometer

$$F = \psi\sigma T_1^4 + (1-\psi)\varepsilon\sigma T_2^4 - \varepsilon\sigma T_2^4$$

$$= \psi\sigma\left[T_1^4 - \varepsilon T_2^4\right]$$ as in equation (1), paragraph IVa.

NOTE

NOTE

I would like to draw attention to the following misprints in Bossy and Pastiels

(a) p. 19, line 6. For $2Evw$ read $2Etv$

(b) p. 105, line 6. For $\frac{E\ell^2 dx dY}{2[(x-Y)^2+\ell^2]^{3/2}}$ read $\frac{E\ell^2 dx dY}{2[(y-Y)^2+\ell^2]^{3/2}}$

(c) p. 108, line 6. For

$$+(t+v)\log\left[(v-w)^2+(t+v)^2+\ell^2\right]$$

read

$$-(t+v)\log\left[(v-w)^2+(t+v)^2+\ell^2\right]$$

(d) p.108, line 15. For

$$-\sqrt{(t-v)^2+\ell^2} \quad \text{read} \quad +\sqrt{(t-v)^2+\ell^2}$$

(e) p.108, line 18. For

$$+\sqrt{(t-v)^2+\ell^2}\log\left[(v-w)^2+(t-v)^2+\ell^2\right]$$

read

$$-\sqrt{(t-v)^2+\ell^2}\log\left[(v-w)^2+(t-v)^2+\ell^2\right]$$

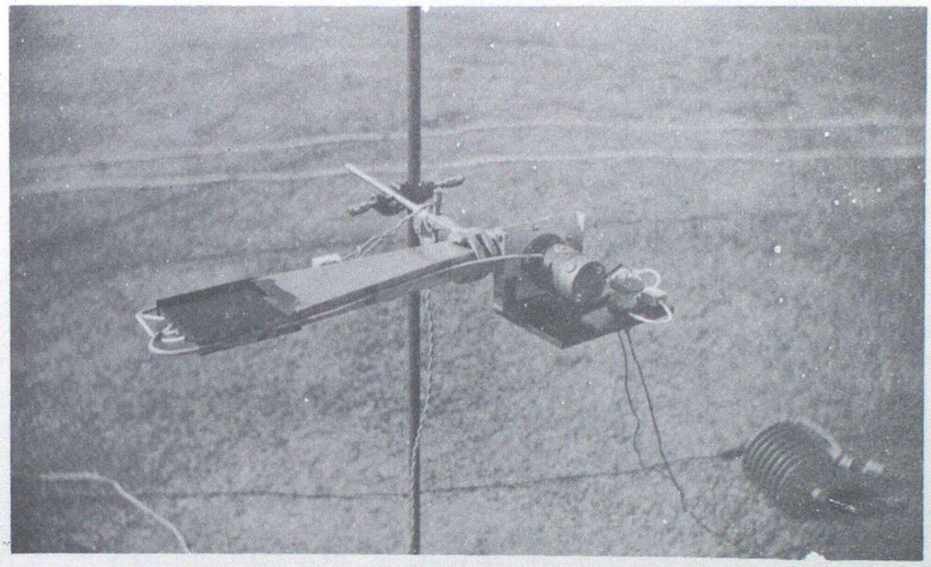

Fig. 1 Complete radiometer.

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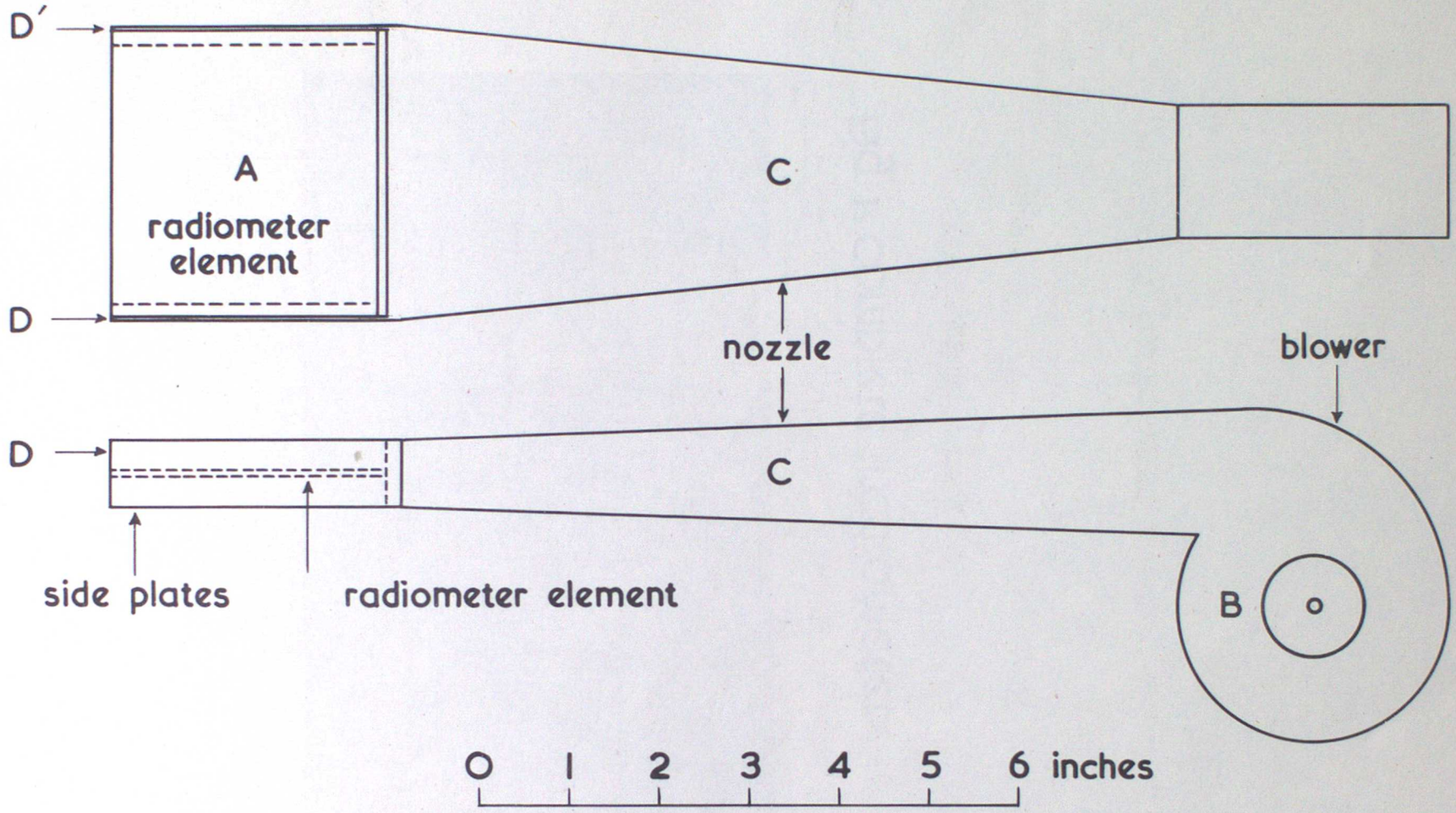


Fig. 2 Complete radiometer

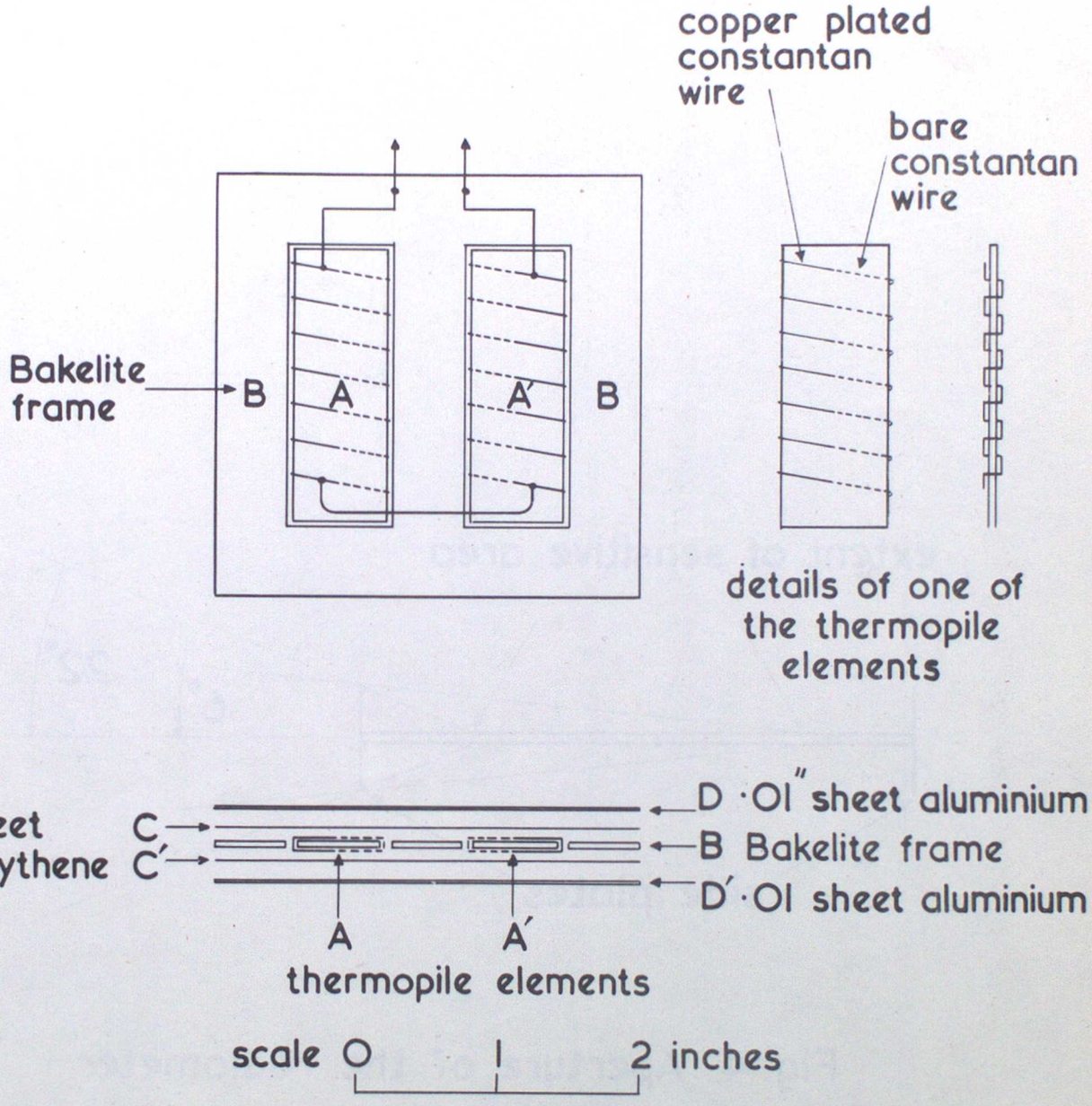


Fig. 3 Radiometer element

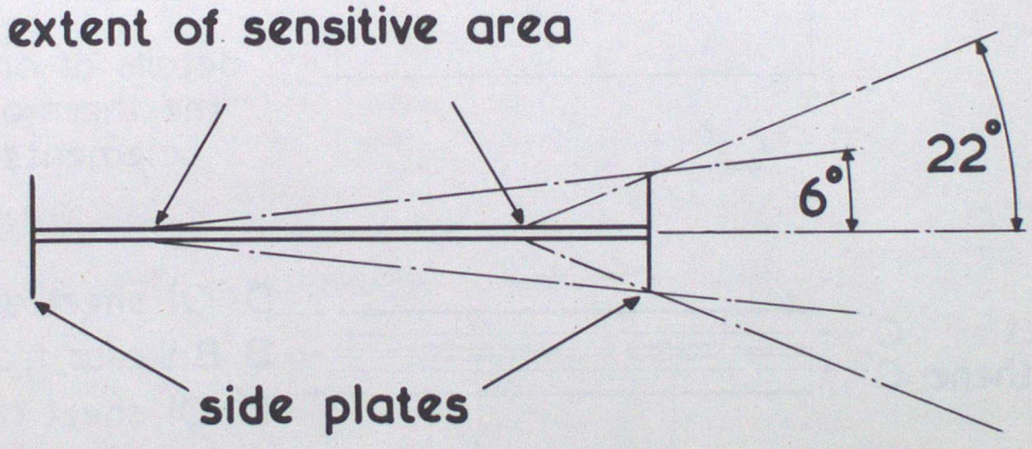


Fig. 4 Aperture of the radiometer

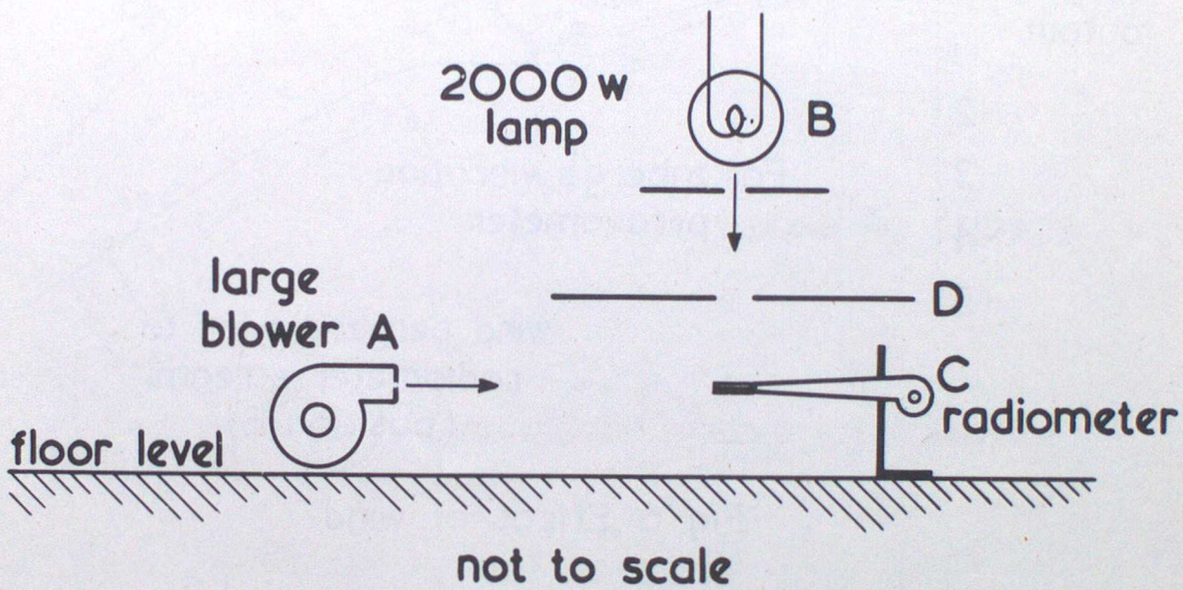


Fig. 5 Experimental arrangement for the determination of wind effect

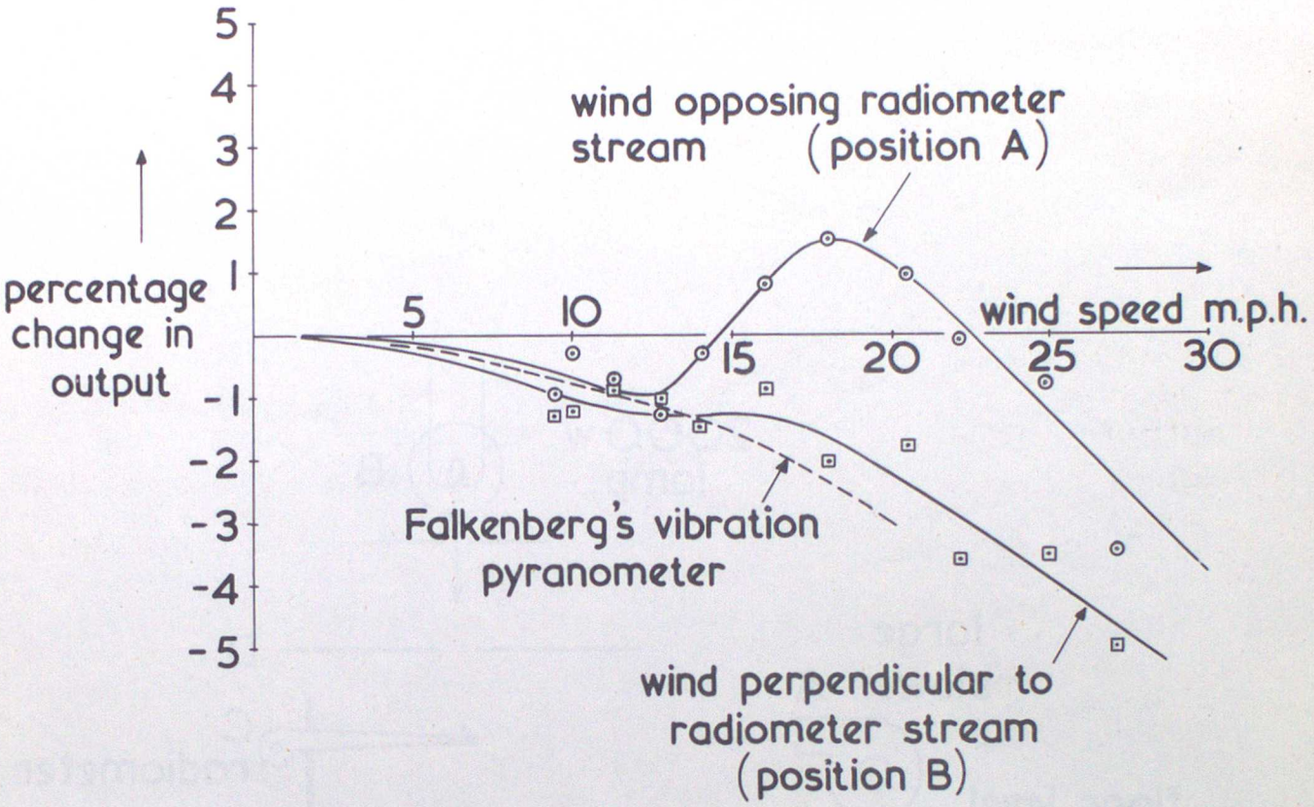


Fig. 6 Effect of wind

position A	
velocity	% change
5·7 m.p.h.	4·8
11·4 ,,	0·0
15·0 ,,	-2·5
19·8 ,,	-16·0
25·0 ,,	-11·0
27·6 ,,	-11·0

position B	
velocity	% change
7·3 m.p.h.	-2·5
9·8 ,,	-3·4
15·3 ,,	-4·2
20·5 ,,	-6·3
23·6 ,,	-8·3

Table I Effect of wind on Gier's radiometer

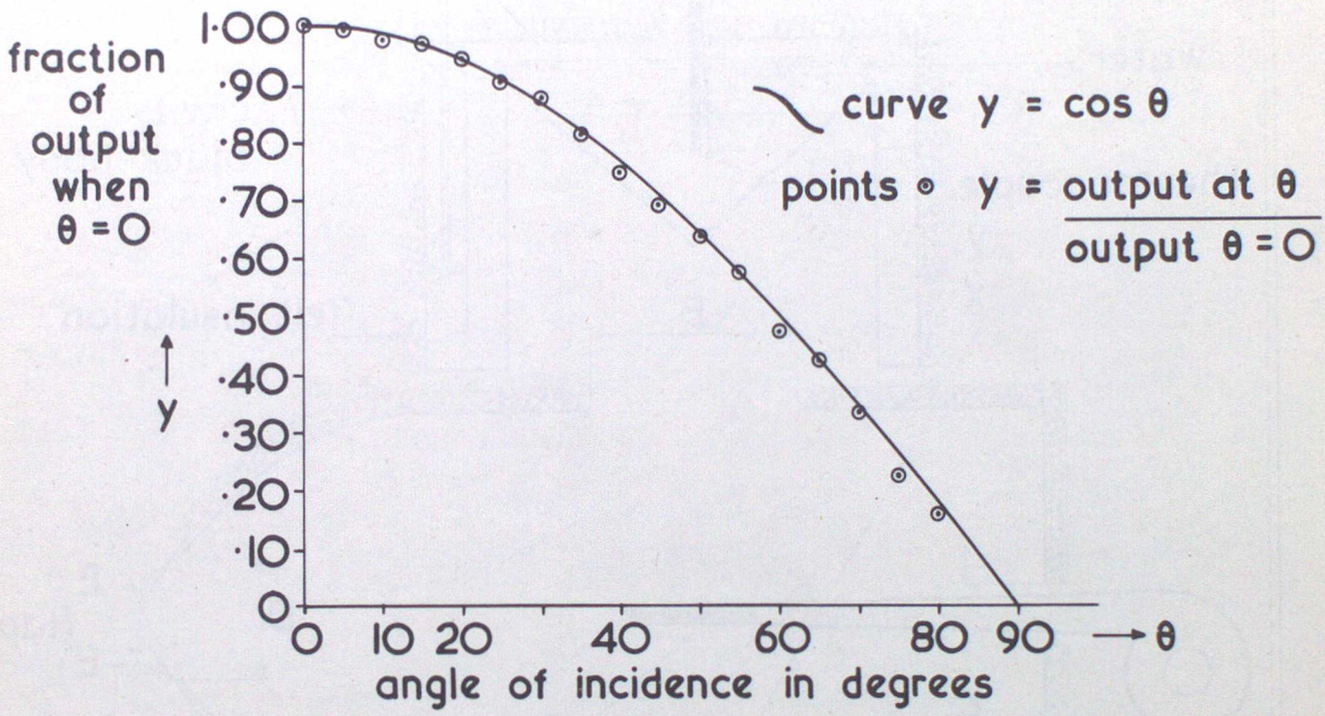


Fig. 7 Cosine characteristic of surface

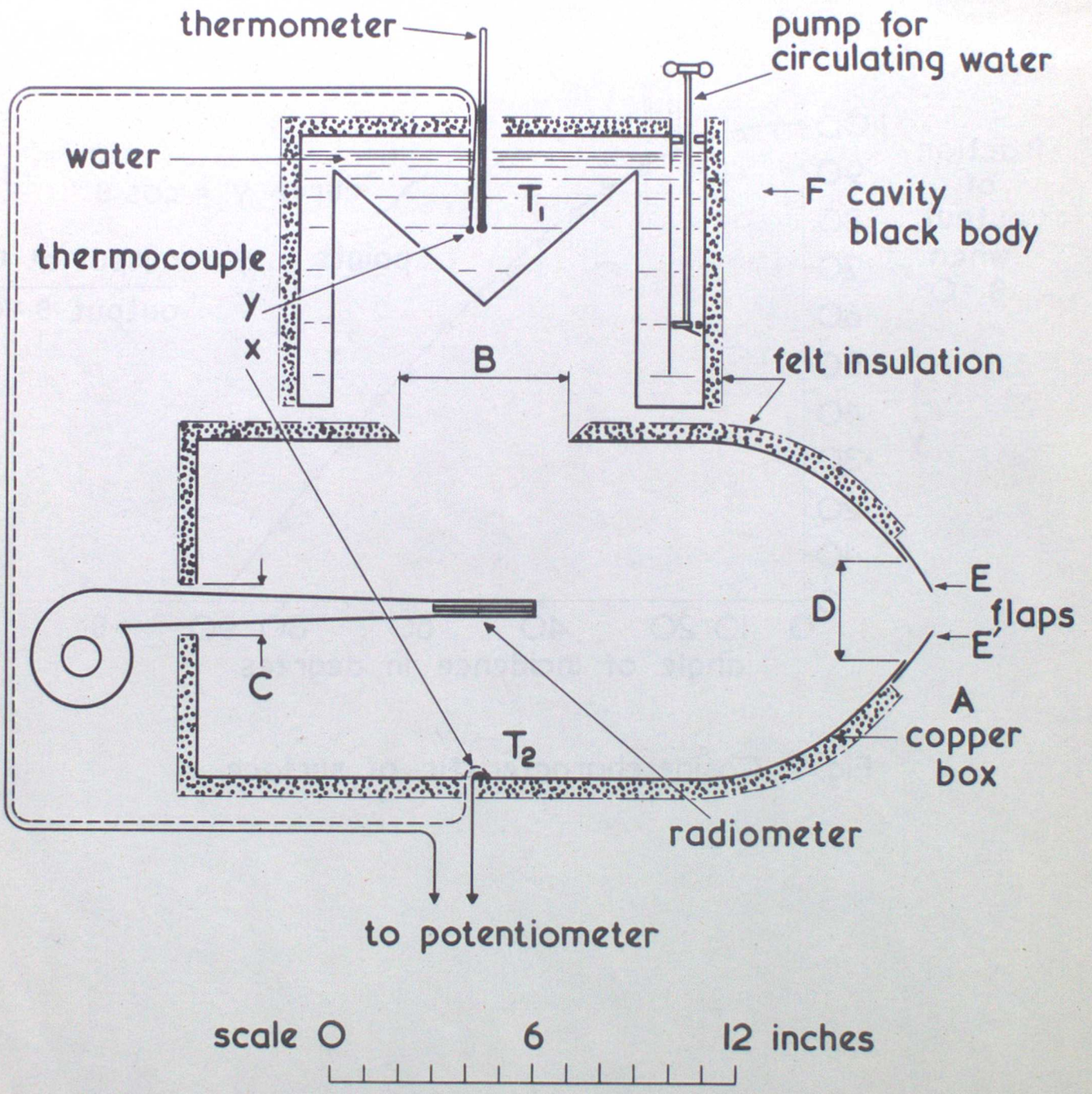


Fig. 8 Radiometer calibration

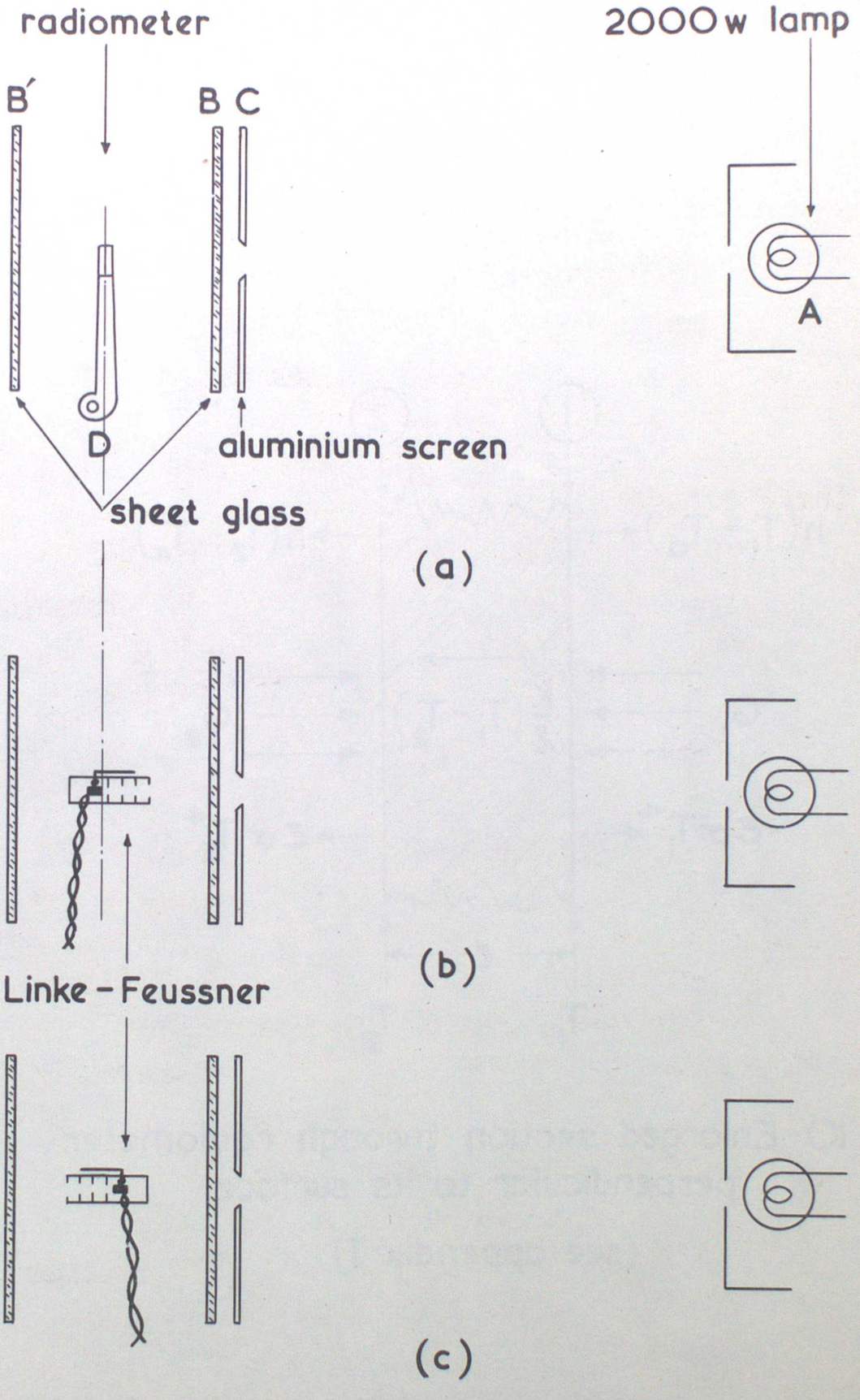


Fig. 9 Radiometer calibration

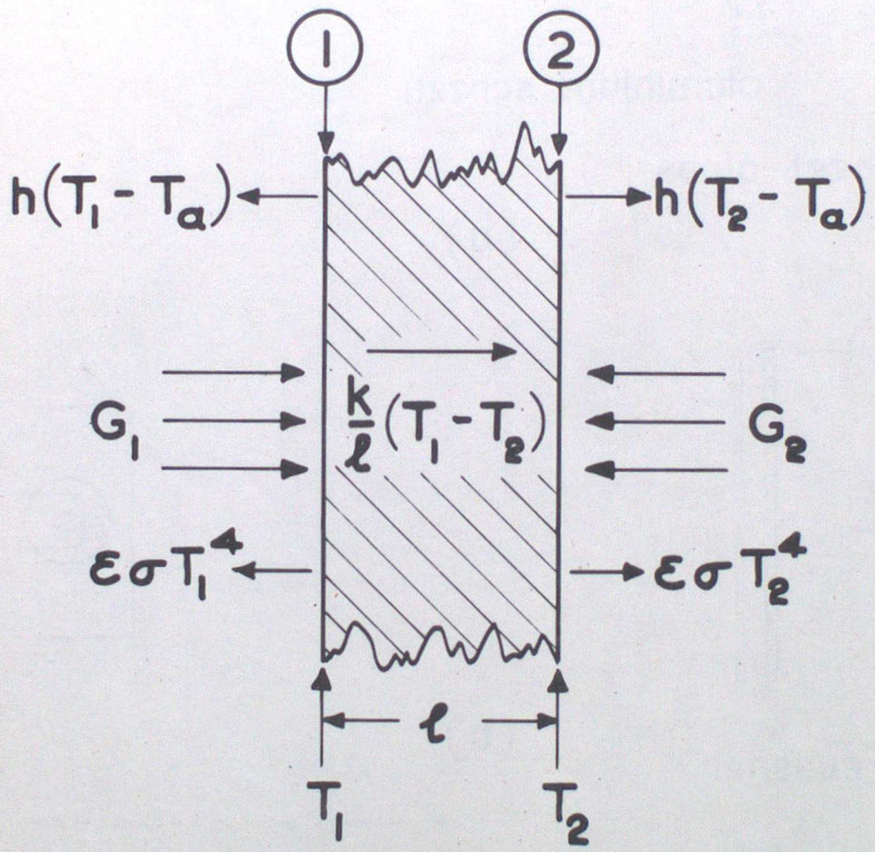
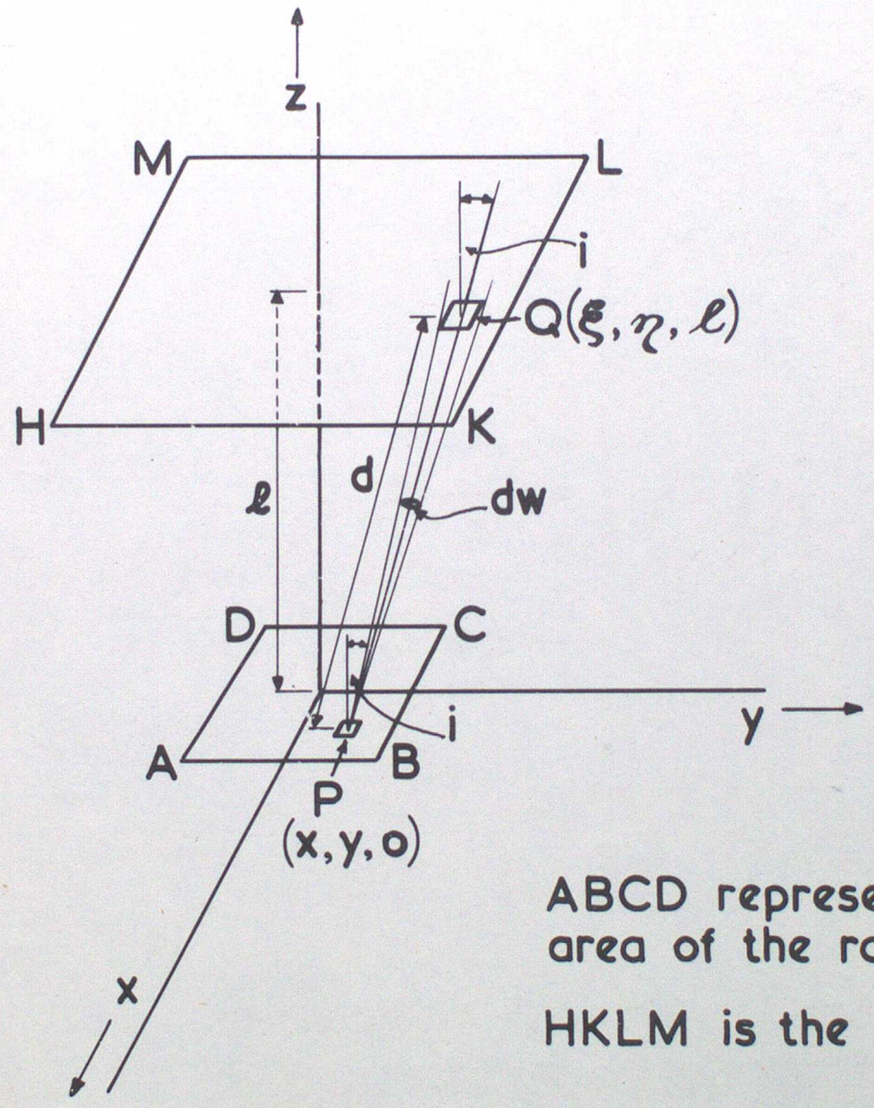


Fig. 10 Enlarged section through radiometer perpendicular to its surface

(see appendix I)



ABCD represents the sensitive area of the radiometer

HKLM is the aperture

Fig. II The aperture – radiometer system (see appendix II)